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Evidence of New States Decaying into $\Xi_c^* \pi$

CLEO Collaboration

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Abstract

Using data recorded by the CLEO II detector at CESR, we report preliminary evidence for two new charmed baryons, one decaying into $\Xi_c^+ \pi^+ \pi^-$ via an intermediate Ξ_c^{*0}, and its isospin partner decaying into $\Xi_c^0 \pi^+ \pi^-$ via an intermediate Ξ_c^{*+}. We measure the mass differences $M(\Xi_c^+ \pi^+ \pi^-) - M(\Xi_c^+)$ to be $348.5 \pm 0.5 \pm 1.0$ MeV, and $M(\Xi_c^0 \pi^+ \pi^-) - M(\Xi_c^0)$ to be $348.1 \pm 0.8 \pm 2.0$ MeV. We interpret these new states as the $J^P = \frac{3}{2}^-$ Ξ_{c1} particles, the charmed-strange analogues of the $\Lambda_{c1}^+(2625)$.

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In recent years there has been great progress in charmed baryon spectroscopy. Three experiments [1] have now seen a doublet of particles decaying into $\Lambda_c^+\pi^+\pi^-$, and the consensus is that these states are the lowest lying orbitally excited states of the Λ_c^+. The quark model picture of these excited Λ_c^+ baryons is that they consist of a light diquark which has one unit of orbital angular momentum with respect to the heavy (charmed) quark, leading to a $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ doublet. They are now commonly referred to as the Λ_{c1}^+ particles [2], where the numerical subscript refers to the total angular momentum of the light degrees of freedom. Clearly similar orbital excitations must exist in the Ξ_c^+ sector. Using data from the CLEO II detector, we presented in 1997 [3] first evidence for a new state decaying into $\Xi_c^+\pi^+\pi^-$ via an intermediate Ξ_c^{*0}, and we identified this state as the $J^P = \frac{3}{2}^-$ Ξ_{c1}^+, which corresponds to a cus quark combination in which the u and s spins are antiparallel and the us diquark has orbital angular momentum $L = 1$ with respect to the charmed quark. In the last year we have reanalyzed the same data sample. This new analysis includes mass dependent fitting of the particle trajectories taking into account energy loss throughout the detector, improved secondary and tertiary vertex detection, and an increase in the number of Ξ_c decay modes used for Ξ_c^* reconstruction. We now present further evidence and new measurements of the Ξ_{c1}^+ as well as first evidence of its isospin partner, the Ξ_{c1}^0, by its decay to $\Xi_c^0\pi^+\pi^-$ via an intermediate Ξ_c^{*+}.

The data presented here were taken by the CLEO II detector [4] operating at the Cornell Electron Storage Ring. The sample used in this analysis corresponds to an integrated luminosity of 4.8 fb^{-1} from data taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just above and below the $\Upsilon(4S)$. We detected charged tracks with a cylindrical drift chamber system inside a solenoidal magnet. Photons were detected using an electromagnetic calorimeter consisting of 7800 cesium iodide crystals.

We first obtain large samples of reconstructed Ξ_c^+ and Ξ_c^0 particles, using their decays into Λ, Ξ^-, Ω^- and Ξ^0 hyperons as well as K's, π's and protons[1]. A combination of energy-loss measurements in the drift chamber and time-of-flight measurements are used to help identify the stable charged particles.

Candidates for Λ decays are reconstructed from $p\pi^-$ combinations, that intersect at a point displaced from the primary event vertex. The Λ candidates are required to have a measured invariant mass within 5.0 MeV/c^2 (about three standard deviations) of the known Λ mass.

$\overline{K}^0$ candidates are reconstructed from observing the decay $K_s^0 \to \pi^+\pi^-$. The two π tracks are required to intersect at a point displaced from the primary vertex, and each daughter track was required to be inconsistent with originating from the primary vertex. The K_s^0 candidates were required to have a measured invariant mass within 8.0 MeV (about three standard deviations) of the known K_s^0 mass.

The Ξ^- candidates are formed by combining each Λ candidate with each remaining negatively charged track A vertex is formed from the intersection of the Λ track and the negatively charged track. We require that the measured flight path of the reconstructed Ξ^- be greater than 2 mm, that the reconstructed Ξ^- be consistent with coming from the main

[1]Charge conjugate states are implied throughout.

event vertex, and the measured distance between the event vertex and the Ξ^- decay point be less than the distance between the event vertex and the Λ vertex. Combinations with a measured invariant mass within 5 MeV/c^2 (about three standard deviations) of the known Ξ^- mass are kinematically fit to this mass and used to reconstruct Ξ_c^+ candidates.

Candidates for Ξ^0 baryons are formed by combining each Λ candidate with each π^0 candidate. These π^0 candidates are formed from photon pairs detected in the CsI calorimeter. As a first approximation they are assumed to come from the event vertex and only a loose cut is applied on the $\gamma\gamma$ invariant mass. The Λ candidates used for Ξ^0 reconstruction are required to have a measured flight path greater than 5 mm and not to point back to the event vertex. The Ξ^0 is assumed to be created at the event vertex, and to have a momentum equal to the sum of the momenta of the Λ and π^0 candidates. The decay point of the Ξ^0 is taken to be the point of intersection between the Ξ^0 candidate and the Λ candidate. This decay point is required to be at least 3 mm from the event vertex. The 4-momentum of the π^0 candidate was recalculated using the Ξ^0 decay point, rather than the primary vertex, as the point of origin of the photons, and its mass is required to be consistent ($< 3.5\sigma$) with the known π^0 mass. The $\Lambda\pi^0$ invariant mass is then recalculated using this improved estimate of the π^0 momentum, and those combinations within 8 MeV/c^2 ($\approx 3\sigma$) of the known Ξ^0 mass are kinematically fit to this mass and used to reconstruct Ξ_c^+ baryons.

For the purpose of illustrating the good statistics and signal to noise ratio of the Ξ_c signals, and to reduce the combinatorial background, we have placed a cut $x_p > 0.5$, where $x_p = p/p_{max}$, p is the momentum of the charmed baryon, $p_{max} = \sqrt{E_{beam}^2 - M^2}$, where M is the calculated Ξ_c mass, and E_{beam} is the beam energy. We fitted the invariant mass distributions for these modes to a sum of a Gaussian signal and a second order polynomial background. The yields from each of the decay modes we used are summarized in Table 1. We note that this is the first observation of the decay modes $\Xi_c^+ \to \Lambda\overline{K}^0\pi^+$ and $\Xi_c^0 \to \Lambda K^-\pi^+$. The x_p cut used for Figure 1 was not used in the final analysis, as we prefer to apply an x_p cut only on the $\Xi_c\pi^-\pi^+$ combinations. However, the value of 0.5 for the x_p cut on the Ξ_c results in a similar Ξ_c sample as used in the final analysis.

The Ξ_c candidates defined above were then combined with each remaining charged track in the event and the mass differences $\Delta(M)= M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ and $M(\Xi_c^0\pi^+) - M(\Xi_c^0)$ were calculated. We consider those combinations within 5 MeV of the previously measured Ξ_c^* masses [5] as Ξ_c^* candidates.

We then combine these Ξ_c^* candidates with one more correctly charged tracks in the event and plot $M(\Xi_c\pi^-\pi^+) - M(\Xi_c)$ for both the Ξ_c^+ (Figure 2a) and the Ξ_c^0 Figure 2b, with an $x_p > 0.6$ on the final combination. Because charmed particles produced in e^+e^- annihilation are known to have a hard momentum spectrum, whereas background combinations lie mostly at low momentum, this cut eliminates a large fraction of the background while retaining a good fraction of signal. We prefer to present the data as a dipion mass difference rather than $M(\Xi_c^*\pi) - M(\Xi_c^*)$ because the latter measurement is complicated by the intrinsic width of the Ξ_c^*, which is not well known. In both cases there is a peak at around 348 MeV. We fit these two peaks to sums of Gaussians of fixed width ($\sigma = 1.8$ MeV, found from a Monte Carlo program), and a polynomial background function. For the charged case, we find a signal of 18.8 ± 4.4 events at a $\Delta(M)$ of 348.5 ± 0.5 MeV, consistent with the results of our previous analysis [3]. For the neutral case, we find an excess of 9.5 ± 3.2 events with a $\Delta(M)$

of 348.1 $\pm$ 0.8 MeV. Both peaks are satisfactorily fit with this fitting function, however, to investigate the natural widths of the states, we have also fit to a Breit-Wigner function convoluted with a Gaussian resolution function. This gives limits to the natural widths of the states to be $\Gamma < 3.5$ MeV and $\Gamma < 8.1$ MeV respectively, each at the 90% confidence level. We estimate the systematic uncertainty on the measured mass differences to be 1 MeV and 2 MeV respectively. This estimate takes into account the spread of results obtained using different fitting functions as well as uncertainties in the momentum measurements.

In order to check that all the Ξ_{c1} decays proceed via an intermediate Ξ_c^*, we release the cuts on $M(\Xi_c\pi) - M(\Xi_c)$, select combinations within 5 MeV of our final signal peaks and plot $M(\Xi_c\pi) - M(\Xi_c)$. Both plots (Figure 4) show signals which were fit to a Breit-Wigner convoluted to a Gaussian resolution function, plus a flat background. The masses and widths for the Ξ_c^* particles found in this way are consistent with our previously published results. It is clear that our data is consistent with all our Ξ_{c1} decays proceeding via an intermediate Ξ_c^*.

Although the statistics are very limited, they are sufficient to do a rough investigation of the momentum spectrum with which the new particles are produced. We add the two isospin states together as we would expect them to have very similar momentum distributions. We relax the x_p cut from 0.6 to 0.5, and fit the dipion mass difference plots (Figure 3) in bins of x_p. The fit uses a fixed width derived from the Monte-Carlo study, with the mass fixed at the value found for $x_p > 0.6$. The yields in each bin of x_p were corrected for the detector efficiency, and the resulting x_p distribution shown in Figure 5. The fit to this spectrum is of the functional form due to Peterson *et al.* [10]. The fitted parameter ϵ_r is measured to be $\epsilon_r = 0.07^{+.03}_{-.02}$. This value is very similar to that found for the Λ_{c1}^+ spectrum [1], and harder than those found for charmed baryons with no orbital angular momentum.

There has been little theoretical work in recent years on the spectroscopy of orbitally excited Ξ_c states. However, the models [6] that do exist predict that the excitation energy of the first orbitally excited doublet should be similar to the analogous value in the Λ_c^+ case (308 and 342 MeV for the two states). Furthermore the decay patterns of the Ξ_{c1} states should be closely analogous to those of the Λ_{c1}^+. The preferred decay of the $J^P = \frac{3}{2}^-$ Ξ_{c1} should be to $\Xi_c{}^*\pi$ because the spin-parity of the baryons allows this decay to proceed via an S-wave decay. Decays to Ξ_c' would have to proceed via a D-wave and would therefore be suppressed. In the case of the $J^P = \frac{1}{2}^-$ Ξ_{c1} the situation is reversed. It is natural therefore to expect a particle found by its decay to $\Xi_c^*\pi$ to have $J^P = \frac{3}{2}^-$. When the total spin and parity of the baryon is considered, decays directly to the ground state with one transition π, not allowed for the Λ_{c1}^+ because of isospin conservation, are allowed for the Ξ_{c1} via a D-wave. Taking into account the large phase space available, such decays might be expected to be large. However, in the Heavy Quark Effective Theory theory [9], where the angular momentum and parity of the light di-quark degrees of freedom must be considered separately from the heavy quark, such decays are forbidden. Thus in the HQET picture, we would expect that the dominant decay of a $J^P = \frac{3}{2}^-$ Ξ_{c1}^+ would be to $\Xi_c^{*0}\pi^+$, consistent with our observation. Following our first analysis of the Ξ_{c1}^+, there have been two papers that include theoretical calculations of the expected Ξ_{c1} widths. Yan and Pirjol [7] calculate $2.37 - 15.00$ MeV, whereas Chiladze and Falk [8] calculate $5.4^{+3.8}_{-2.5}$ MeV. Both calculations use the experimentally measured width of the $\Lambda_{c1}(2593)$ as input. Our results favour a natural width for each of the Ξ_{c1} particles at

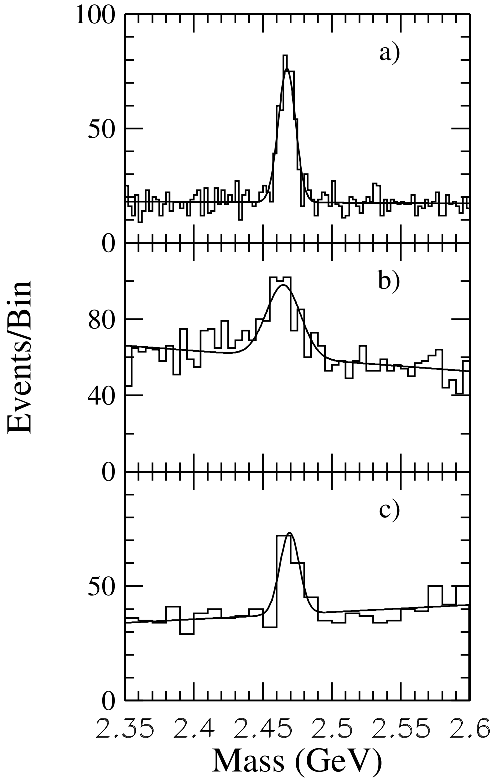

FIG. 1. Mass spectra for (a) $\Xi^- \pi^+ \pi^+$ combinations, (b) $\Xi^0 \pi^+ \pi^0$ combinations, and (c) $\Lambda \overline{K^0} \pi^+$. In all cases clear Ξ_c^+ peak can be seen. There is an x_p cut of 0.5 applied.

the lower end of these predictions.

In conclusion, we present evidence for the production of two new states. The first of these states decay into $\Xi_c^{*0} \pi^+$ with measured mass of the new state is given by $M(\Xi_c^+ \pi^- \pi^+) - M(\Xi_c^+) = 349.4 \pm 0.7 \pm 1.0$ MeV, and its width is $\Gamma < 3.5$ MeV at the 90% confidence level. The second state decays into $\Xi_c^{*+} \pi^-$ with a mass given by $M(\Xi_c^0 \pi^+ \pi^-) - M(\Xi_c^0) = 348.1 \pm 0.8 \pm 2.0$ MeV. Although we do not measure the spin or parity of these states, the decay modes, masses, and momentum distribution are all consistent with the new states being the $J^P = \frac{3}{2}^-$ Ξ_{c1}^+ and Ξ_{c1}^0 states, the charmed-strange analogues of the $\Lambda_{c1}^+(2625)$.

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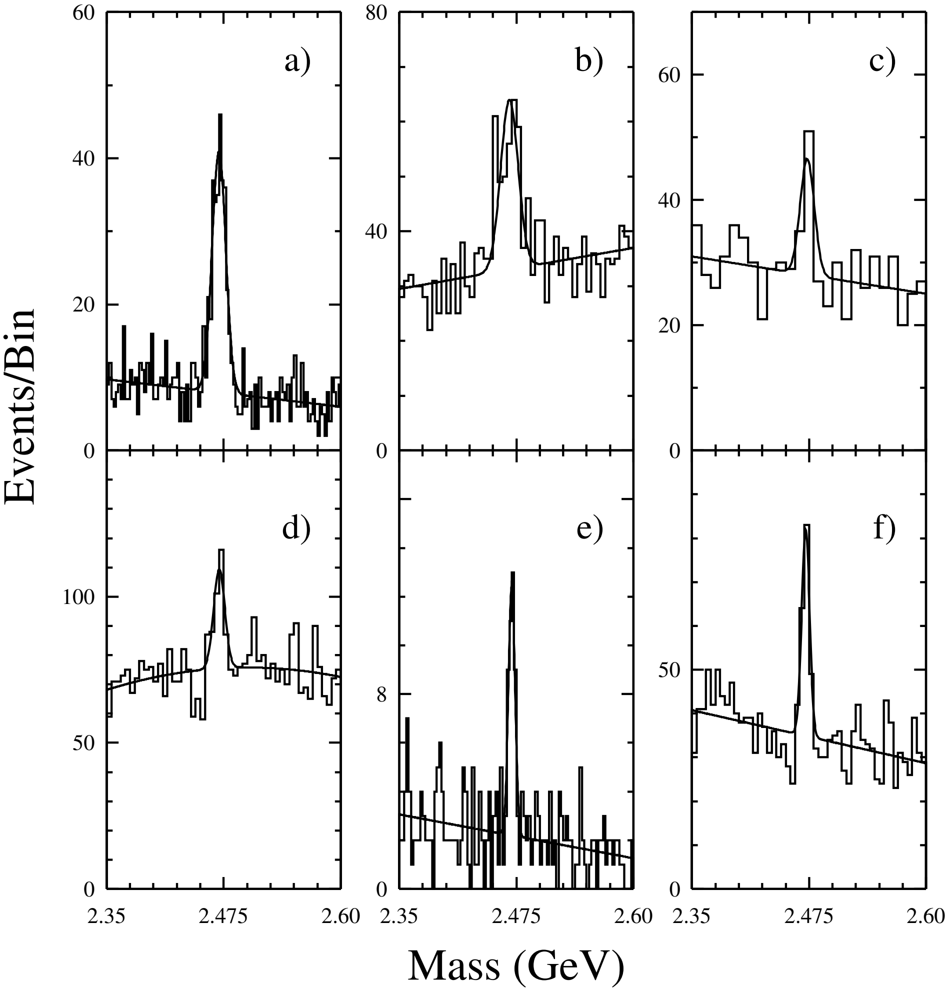

FIG. 2. Mass spectra for (a) $\Xi^-\pi^+$ combinations, (b) $\Xi^-\pi^+\pi^0$ combinations, (c) $\Lambda\overline{K^0}$ combinations, (d) $\Xi^0\pi^+\pi^-$ combinations, (e) Ω^-K^+ combinations, and (f) $\Lambda K^-\pi^+$ combinations. In all cases clear Ξ_c^0 peaks can be seen. There is an x_p cut of 0.5 applied.

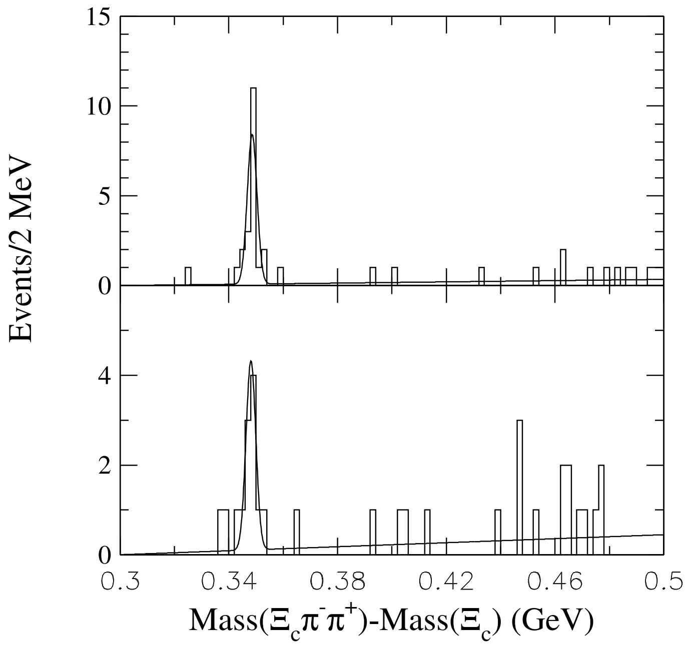

FIG. 3. (a)The mass difference $M(\Xi_c^+\pi^+\pi^-) - M(\Xi_c^+)$ for combinations that lie in the Ξ_c^{*0} band. and (b) the mass difference $M(\Xi_c^0\pi^+\pi^-) - M(\Xi_c^0)$ for combinations that lie in the Ξ_c^{*+} band. In both cases an $x_p > 0.6$ cut is applied.

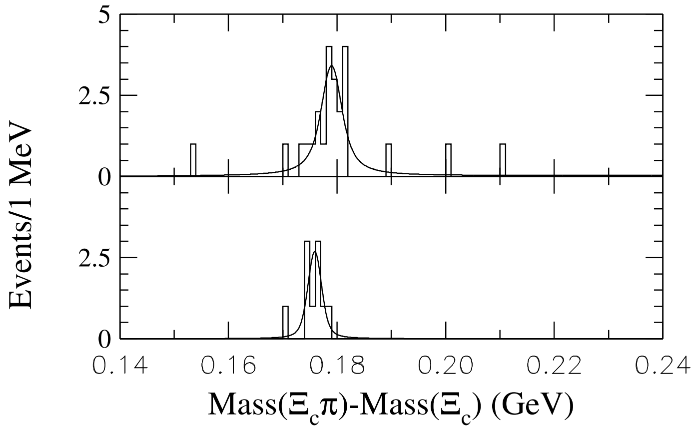

FIG. 4. After selecting combinations in the signals shown in Figure 2, we plot (a) $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ and (b) $M(\Xi_c^0\pi^+) - M(\Xi_c^0)$. Clear Ξ_c^* peaks are seen in both plots.

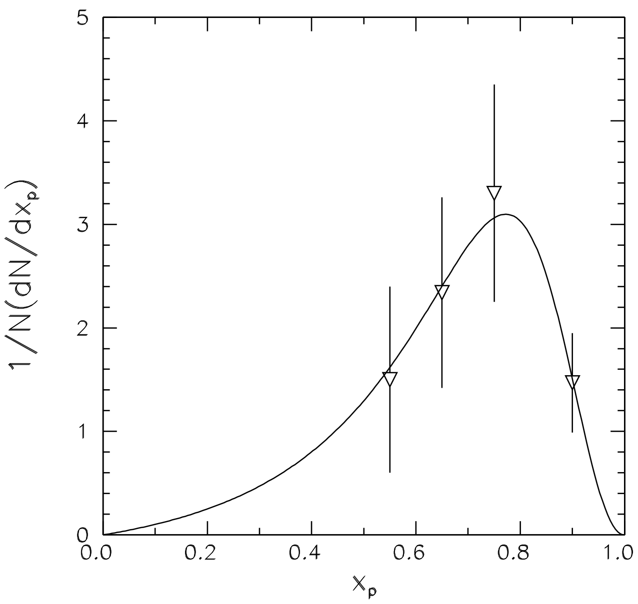

FIG. 5. Scaled momentum distribution of the new particles. The fit is of the form of the Peterson function.